

UNIVERSITÀ POLITECNICA DELLE MARCHE Repository ISTITUZIONALE

Direct computation of aeroacoustic fields in laminar flows: Solver development and assessment of wall temperature effects on radiated sound around bluff bodies

This is the peer reviewd version of the followng article:

Original

Direct computation of aeroacoustic fields in laminar flows: Solver development and assessment of wall temperature effects on radiated sound around bluff bodies / D'Alessandro, V.; Falone, M.; Ricci, R. - In: COMPUTERS & FLUIDS. - ISSN 0045-7930. - ELETTRONICO. - 203:(2020). [10.1016/j.compfluid.2020.104517]

Availability:

This version is available at: 11566/277428 since: 2024-10-28T11:33:22Z

Publisher:

Published DOI:10.1016/j.compfluid.2020.104517

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. The use of copyrighted works requires the consent of the rights' holder (author or publisher). Works made available under a Creative Commons license or a Publisher's custom-made license can be used according to the terms and conditions contained therein. See editor's website for further information and terms and conditions. This item was downloaded from IRIS Università Politecnica delle Marche (https://iris.univpm.it). When citing, please refer to the published version.

Direct computation of aeroacoustic fields in laminar flows: solver development and assessment of wall temperature effects on radiated sound around bluff bodies

Valerio D'Alessandro^{a,*}, Matteo Falone^a, Renato Ricci^a

^aDipartimento di Ingegneria Industriale e Scienze Matematiche Università Politecnica delle Marche Via Brecce Bianche, 60131 Ancona (AN), Italy

1 Abstract

This work presents results of a direct computation of acoustic fields produced by 2 several laminar flow configurations. A solver specifically developed for compress-3 ible mass, momentum and energy equations, named caafoam, is presented. Low-4 storage high-order Runge-Kutta schemes were used for time integration, and an un-5 structured colocated finite-volume method for space discretization. A sponge-laver-6 type non-reflective boundary treatment was adopted to avoid spurious numerical 7 reflections at the far-field boundaries. These techniques were chosen and tested to 8 see if they enable a broad range of physical phenomena, with a particular emphasis 9 on aeroacoustic problems, to be solved. The reliability, efficiency and robustness of 10 caafoam was demonstrated by computing several benchmarks concerning far-field 11 aerodynamic sound. After proving the direct simulation capabilities of caafoam, it 12 was used to analyze the effect of the wall temperature conditions on the aeroacoustic 13 sound produced by laminar flows over bluff bodies. 14

¹⁵ Key words:

¹⁶ OpenFOAM, Aeroacoustics, Direct Numerical Simulation, Bluff body, Active

¹⁷ sound reduction

18 1 Introduction

The study of noise radiated from objects is a key engineering problem because
the noise itself can have significant negative effects on our daily lives.

From the engineering standpoint, it is essential to understand the mechanisms of aeroacoustic noise generation and propagation in order to achieve its control/reduction. A number of experimental efforts have been devoted to this issue, but they have met with a few problems relating to aeroacoustic noise. It is really difficult, for instance, to remove background noise that contaminates the aeroacoustic field.

²⁷ Computational aeroacoustic (CAA) techniques can be a reliable way to study ²⁸ aerodynamically-produced sound [1]. They involve several approaches; how-²⁹ ever our interests are devoted to the direct numerical simulation (DNS) of the ³⁰ aeroacoustic sound, where the flow generating the sound and its propagation ³¹ are both solved computationally.

DNS can encounter several difficulties, largely because the sound pressure 32 is usually much smaller than the ambient pressure [2]. In addition, acous-33 tic waves are reflected at the far boundaries of the domain when standard 34 boundary conditions are employed and, for DNS computations, ad hoc non-35 reflecting boundary conditions are needed to fix this issue [3]. To prevent 36 numerical dissipation and dispersion from overshadowing sound production, 37 DNS computations have traditionally been done using high-order methods, 38 such as finite difference (FD) [4], finite volume (FV) [5] or, more recently, dis-39 continuous Galerkin (DG) methods [6]. For the same reasons, Runge-Kutta 40 (RK) methods are used for time integration. It is worth noting that high-order 41 FD (based on compact schemes) and FV methods carry a loss of parallel effi-42 ciency due to a non-compact stencil. On the other hand, the theoretical order 43 of accuracy is not preserved when dealing with irregular grids, or at the phys-44

^{*} Corresponding author.

Email address: v.dalessandro@univpm.it (Valerio D'Alessandro).

ical boundaries. DG methods are more flexible than FV or FD approaches,
but they carry a huge computational resource demand [7]. High-order methods have been also employed by CAA investigators since they allow to resolve
waves propagation phenomena with the minimum number of mesh points per
wavelength [3]. Differently, standard second-order schemes require a grater
number of mesh points per wavelength to ensure adequate accuracy. Thus,
they are not considered as the cutting-edge solution strategy in CAA.

All the above-mentioned high-resolution methods are typically adopted in 52 academic codes with a very limited dissemination to the general public. That 53 is why we have developed an open-source solver for aeroacoustic DNS to 54 publicize the feasibility of performing such computations. Our CAA solver, 55 named **caafoam**, is free to download on GitHub at the following address: 56 https://github.com/vdalessa/caafoam. It employs low-storage high-order Runge-57 Kutta (RK) schemes for time integration, with an accurate artificial sponge-58 layer-type, non-reflective boundary treatment. The governing equations are 59 space-discretized using an unstructured colocated FV method in order to ex-60 ploit the solver's flexibility in handling complex geometries. Moreover, our 61 second order approach is also intended as extending the OpenFOAM library 62 capabilities for CAA and compressible flows and it is also conceived as a step-63 ping stone to higher order implementations in OpenFOAM. 64

The solver has been validated, also by comparing its performance with other
freely-available tools, to demonstrate its reliability, efficiency and robustness.
Particularly, in the considered cases the sound radiated from bluff bodies in a
uniform undisturbed flow is directly simulated.

The impact of the thermal boundary conditions on sound propagation is also investigated. It was shown that the wall temperature increment can reduce the lift and drag pulsations and increase the drag generated by the Karman vortex street that is shed over bluff bodies in laminar flows. In the available literature, similar effects had already been noted by Lecordier et al. [8, 9]. In the present context, however, any reduction in lift pulsations is very important ⁷⁵ because it leads to a decay in aeroacoustic perturbations.

This paper is organised as follows: the governing equations are presented in
Section 2, while the adopted numerical discretization techniques are discussed
in Section 3; Section 4 is devoted to numerical results. Lastly, Section 5 contains the conclusions.

80 2 Governing equations

89

The flow model adopted in this work concerns the unsteady mass, momentum 81 and energy equations. Let $t \in [0, T]$ be a given instant in the temporal domain, 82 $\mathbf{x} \in \Omega \subset \mathbb{R}^d$ (with d = 2, 3) a given point in the spatial domain, and Q =83 $\Omega \times [0,T] \subset \mathbb{R}^d \times \mathbb{R}^+$. The initial boundary values problem consists in finding 84 the solution vector \mathbf{u} : $Q \to \mathbb{R}^{d+2}$ that, for the given Dirichelet boundary 85 conditions \mathbf{u}_D : $\Gamma_D \times [0,T] \to \mathbb{R}^{d+2}$, Neumann boundary conditions \mathbf{h}_N : 86 $\Gamma_N \times [0,T] \to \mathbb{R}^{d+2}$, and initial conditions $\mathbf{u}_0 : \Omega \to \mathbb{R}^{d+2}$, satisfy the governing 87 equations: 88

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}_{\mathbf{c},j}}{\partial x_j} = \frac{\partial \mathbf{f}_{\mathbf{v},j}}{\partial x_j} \quad \text{in } Q,$$

$$\mathbf{u} = \mathbf{u}_D \quad \text{on } \Gamma_D \times [0,T],$$

$$\frac{\partial \mathbf{u}}{\partial x_j} n_j = \mathbf{h}_N \quad \text{on } \Gamma_N \times [0,T],$$

$$\mathbf{u} = \mathbf{u}_0 \quad \text{in } \Omega \subset \mathbb{R}^d, t = 0,$$
(1)

where $\Gamma = \Gamma_D \bigcup \Gamma_N$ is the boundary of the domain Ω ; Γ_D and Γ_N are the Dirichelet and Neumann boundaries, respectively; and n_j are the components of the outward-facing unit normal vector on Γ .

Relying on the vector $\mathbf{u} = (\rho, \rho u_1, \rho u_2, \rho u_3, \rho E)^T$, the j-th component of the

⁹⁴ convective and diffusive fluxes reads:

$$\mathbf{f}_{\mathbf{c},j} = \begin{pmatrix} \rho u_j \\ \rho u_1 u_j + p \delta_{1j} \\ \rho u_2 u_j + p \delta_{2j} \\ \rho u_3 u_j + p \delta_{3j} \\ \rho u_j H \end{pmatrix}, \quad \mathbf{f}_{\mathbf{v},j} = \begin{pmatrix} 0 \\ \tau_{1j} \\ \tau_{2j} \\ \tau_{3j} \\ \tau_{ji} u_i - q_j \end{pmatrix}.$$
(2)

95

In these relations, ρ denotes the density, u_i is the generic Cartesian component of the velocity vector \mathbf{v} , and p is the pressure. E is the total internal energy, while the total enthalpy is obtained from $H = E + p/\rho$. The viscous stress tensor is computed using the standard constitutive relation for Newtonian fluids:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij}$$
(3)

and the heat flux vector components by means of the Fourier postulate: 102 $q_i = -\lambda \frac{\partial T}{\partial x_i}$. Note that μ is the dynamic viscosity and λ the thermal con-103 ductivity which in this work are modeled as temperature independent. The 104 fluid temperature, T, is measured starting from the total internal energy as 105 follows: $c_v T = E - \frac{1}{2} \mathbf{v} \cdot \mathbf{v}$, where c_v is the specific heat at constant volume. 106 Lastly, the pressure is computed by adopting the ideal gas equation of state 107 as a thermodynamic model: $p = \rho (\gamma - 1) \left(E - \frac{1}{2} \mathbf{v} \cdot \mathbf{v} \right)$, where $\gamma = c_p / c_v$ is 108 the specific heat ratio of the fluid. 109

110 2.1 Non-reflective boundary treatment

As discussed in Section 1, to compute acoustic wave propagation phenomena we need to avoid spurious numerical sound waves produced by external boundaries of the domain. An artificial sponge layer [10, 11] is used for this purpose. The sponge treatment has been widely used because it is simple, robust and flexible in handling complex geometries [12]. Taking this approach,
the governing equations are modified as follows:

117

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}_{\mathbf{c},j}}{\partial x_j} - \frac{\partial \mathbf{f}_{\mathbf{v},j}}{\partial x_j} = \sigma \left(\mathbf{u}_{ref} - \mathbf{u} \right) \quad \text{in } Q \tag{4}$$

The new non-physical term on the right-hand side of eq. 4 is only active near the external boundaries, where it dampens the flow variables to a known reference solution, \mathbf{u}_{ref} . In eq. 4, the scalar field $\sigma : \Omega \to \mathbb{R}$ is:

$$\sigma = \sigma_0 \left(\frac{L_{sp} - d}{L_{sp}}\right)^n \tag{5}$$

where L_{sp} is the thickness of the layer, d is the minimum distance from the 122 nearest far-field boundary, σ_0 is a constant value, and n is an integer parameter 123 controlling the shape of the sponge's profile. An optimal sponge layer design 124 is not trivial: larger sponges perform better than equally-strong smaller ones. 125 In other words, they dampen flow features more quietly [13]. Larger sponges 126 demand larger computational domains; indeed they must be positioned far 127 enough away from the sound sources to avoid interference phenomena with 128 the flow/acoustic fields. 129

Another possible non-reflective approach consists in the adoption of spongelayers which exploit the numerical dissipation produced by the grid stretching. Despite its conceptual simplicity this technique poses difficulties with regard to the evaluation of the grid stretching entity and grid cells' number needed to be applied in the buffer zone. The specific choice is often related to the computational experience gained on a particular code [14]. For this reason in the following we prefer polynomial sponge-layers.

Mani [13] recently ran a theoretical and numerical analysis on non-reflecting boundary treatments based on polynomial sponge layers. The Author provided several practical guidelines for CFD/CAA practitioners on how to avoid sponge failure. In particular, the non-reflective boundary implementation is ¹⁴¹ based on the following parameter:

142

159

$$\eta_{target} = -\frac{40\log_{10}e}{1 - M_{\infty}^2} \int_{L_{sp}} \sigma d\mathbf{x},\tag{6}$$

where η_{target} is the sponge's strength expressed in dB, and M_{∞} is the Mach number of the undisturbed flow. As an example, a sponge with a strength of 40 dB would dampen the amplitude of an incident sound wave by a factor of 146 100 under one-dimensional conditions. The sponge's thickness must also be 147 established with the following constraint:

$$0.5 \le \frac{L_{sp} \cdot f}{c_{\infty}} \le 2 \tag{7}$$

where f is the sound disturbance frequency, and c_{∞} is its phase speed [13]. For all the computations presented in this paper, we have observed that $\eta_{target} = 40 \text{ dB}$ is needed, so n = 2 in eq. 5 has been selected. Indeed, Mani [13] investigated the effect of n on the sponge performance and it showed that quadratic sponge has best overall performance for η_{target} ranging from 20 dB to 60 dB. Lastly, the dimensionless parameter $(L_{sp} \cdot f)/c_{\infty}$, strictly needed to evaluate sponge width, is fixed equal to 0.5 to limit the computational load.

156 2.2 Computing the distance from far-field boundaries

For the purpose of establishing the distance from far-field (non-reflective) boundaries, we have solved the Eikonal differential equation:

$$\frac{\partial \varphi}{\partial x_i} \frac{\partial \varphi}{\partial x_i} = 1 \quad \text{in } \Omega, \tag{8}$$

where $\varphi : \Omega \to \mathbb{R}$ is the distance field. A homogeneous Dirichelet condition is imposed on the non-reflective boundaries, and a homogeneous Neumann boundary condition elsewhere.

¹⁶³ The Eikonal equation computes the exact distance, defined as the distance

from the boundary normal direction. In other words, the distance can be seen
as an advancing front with a unit velocity in the direction of the boundary
normal. The main advantage of this technique is its good scalability on larger
meshes.

The solution for eq. 8 has thus been obtained by converting it into a hyperbolic problem, adding a pseudo-time term:

$$\frac{\partial \varphi}{\partial \tau} + u_{\varphi,j} \frac{\partial \varphi}{\partial x_i} = 1 \quad \text{in } Q \tag{9}$$

with $u_{\varphi,j} = \partial \varphi / \partial x_j$. The solver for computing far-field distance, named eikonal, is free to download at https://github.com/vdalessa/eikonal. It only has to be run once in the pre-processing stage because we rely on non-moving meshes.

174 3 Numerical approximation

170

175 3.1 Finite volume discretization

In the unstructured, colocated, cell-centered FV method adopted in this work, 176 the computational domain Ω is divided into a set of non-overlapping polyg-177 onal cells. Finite volume discretization is briefly recalled here as it is crucial 178 to discussing the approximation techniques for each term appearing in the 179 discrete equations. In the following expressions, the values of the variables at 180 the center of the cell faces are indicated with the subscript $(\cdot)_f$. The term \mathbf{S}_f 181 is the surface area vector of each mesh face; see Fig. 1 for a schematic repre-182 sentation. 183

Starting from the integration of eq. 4 over each mesh element, K (having boundary ∂K), we obtain:

$$\int_{K} \frac{\partial \mathbf{u}}{\partial t} \, \mathrm{d}\Omega + \int_{\partial K} \left(\mathbf{f}_{\mathbf{c},j} - \mathbf{f}_{\mathbf{v},j} \right) n_{j} \, \mathrm{d}\Gamma = \int_{K} \sigma \left(\mathbf{u}_{ref} - \mathbf{u} \right) \, \mathrm{d}\Omega. \tag{10}$$

The non–linear convective term is discretized as follows:

189

196

$$\int_{\partial K} \mathbf{f}_{\mathbf{c},j} n_j \, \mathrm{d}\Gamma = \sum_{f=1}^{N_f} \left(\mathbf{f}_{\mathbf{c},j} \right)_f n_j \left| \mathbf{S}_f \right| \tag{11}$$

where N_f is the number of faces belonging to the mesh element K. Rewriting the Eulerian terms vector as:

$$\mathbf{f}_{\mathbf{c},j} = u_j \mathbf{u} + \mathbf{f}_{\mathbf{c}_{\mathbf{p},j}} + \mathbf{f}_{\mathbf{c}_{\mathbf{E},j}}$$
(12)

with $\mathbf{f}_{\mathbf{c}_{\mathbf{p},j}} = (0, p\delta_{1j}, p\delta_{2j}, p\delta_{3j}, 0)^T$ and $\mathbf{f}_{\mathbf{c}_{\mathbf{E},j}} = (0, 0, 0, 0, u_j p)^T$, it can be approximated as follows:

¹⁹²
$$\sum_{f=1}^{N_f} \left(\mathbf{f}_{\mathbf{c},j} \right)_f n_j \left| \mathbf{S}_f \right| = \sum_{f=1}^{N_f} \phi_f \mathbf{u}_f + \sum_{f=1}^{N_f} \mathbf{\Lambda}_f^{(1)} \left| \mathbf{S}_f \right| + \sum_{f=1}^{N_f} \phi_f \mathbf{\Lambda}_f^{(2)}$$
(13)

where $\mathbf{\Lambda}_{f}^{(1)} = (0, p, p, p, 0)^{T}$ and $\mathbf{\Lambda}_{f}^{(2)} = (0, 0, 0, 0, p)^{T}$. A first way to handle the three terms on the right-hand side of eq. 13 that we consider here follows the Kurganov-Noelle-Petrova (KNP) approach [15]:

$$\sum_{f=1}^{N_f} \phi_f \mathbf{u}_f = \sum_{f=1}^{N_f} \frac{(\psi \phi \mathbf{u})_f^+ - (\psi \phi \mathbf{u})_f^-}{\psi_f^+ + \psi_f^-} + \frac{\psi_f^+ \psi_f^-}{\psi_f^+ + \psi_f^-} \left(\mathbf{u}_f^+ + \mathbf{u}_f^-\right),$$

$$\sum_{f=1}^{N_f} \mathbf{\Lambda}_f^{(1)} \mathbf{S}_f = \sum_{f=1}^{N_f} \frac{\psi_f^+}{\psi_f^+ + \psi_f^-} \left|\mathbf{S}_f\right| \left(\mathbf{\Lambda}^{(1)}\right)_f^+ + \frac{\psi_f^-}{\psi_f^+ + \psi_f^-} \left|\mathbf{S}_f\right| \left(\mathbf{\Lambda}^{(1)}\right)_f^-, \quad (14)$$

$$\sum_{f=1}^{N_f} \mathbf{\Lambda}_f^{(2)} \mathbf{S}_f = \sum_{f=1}^{N_f} \frac{\left(\psi \phi \mathbf{\Lambda}^{(2)}\right)_f^+ - \left(\psi \phi \mathbf{\Lambda}^{(2)}\right)_f^-}{\psi_f^+ + \psi_f^-}.$$

¹⁹⁷ Note that the term ϕ_f in the above equation represents the velocity flux ¹⁹⁸ through the cells' face, and it is evaluated as: $\phi_f = \mathbf{v}_f \cdot \mathbf{S}_f$. In eq. 14, the ¹⁹⁹ superscript + denotes the face value of the element placed in the direction ²⁰⁰ parallel to the \mathbf{S}_f vector depicted in Fig. 1; and the superscript – the oppo-²⁰¹ site direction. These values are obtained by means of a linear interpolation; ²⁰² for example, the + interpolation for \mathbf{u}_f , *i.e.* \mathbf{u}_f^+ , is simply:

$$\mathbf{u}_{f}^{+} = \left(1 - \frac{\mathbf{S}_{f} \cdot \mathbf{d}_{fN}}{|\mathbf{S}_{f}| |\mathbf{d}_{fN}|}\right) \mathbf{u}_{P} + \frac{\mathbf{S}_{f} \cdot \mathbf{d}_{fN}}{|\mathbf{S}_{f}| |\mathbf{d}_{fN}|} \mathbf{u}_{N},\tag{15}$$

the meaning of \mathbf{d}_{fN} is depicted in Fig. 1. ψ_f^+ and ψ_f^- are associated with the local speed of propagation, and they are calculated as reported in Greenshields et al. [16]:

$$\psi_f^+ = \max\left(|\mathbf{S}_f| \sqrt{\gamma R T_f^+} + \phi_f^+, |\mathbf{S}_f| \sqrt{\gamma R T_f^-} + \phi_f^-, 0\right),$$

$$\psi_f^- = \max\left(|\mathbf{S}_f| \sqrt{\gamma R T_f^+} - \phi_f^+, |\mathbf{S}_f| \sqrt{\gamma R T_f^-} - \phi_f^-, 0\right),$$
(16)

207

216

203

where R is the gas constant.

KNP scheme was selected since: (i) there are no Riemann solvers and characteristic decomposition involved [15]; (ii) it is was already implemented within
OpenFOAM package and repeatedly tested; so it produces a reliable approximate solution of the Riemann problem.

In this paper, we also consider a second approach to approximating the Eulerian numerical flux in which we split $\mathbf{f}_{\mathbf{c},j}$ into a convective and a pressure part:

$$\mathbf{f}_{\mathbf{c},j} = \mathbf{f}_{\mathbf{c}_{\mathbf{H},j}} + \mathbf{f}_{\mathbf{c}_{\mathbf{p},j}} \tag{17}$$

with $\mathbf{f}_{\mathbf{c}_{\mathbf{H},j}} = u_j \left(\rho, \rho u_1, \rho u_2, \rho u_3, \rho H\right)^T$; so FV approximation for $\mathbf{f}_{\mathbf{c},j}$ is:

²¹⁸
$$\sum_{f=1}^{N_f} \left(\mathbf{f}_{\mathbf{c},j} \right)_f n_j \left| \mathbf{S}_f \right| = \sum_{f=1}^{N_f} \left(\mathbf{f}_{\mathbf{c}_{\mathbf{H},j}} \right)_f n_j \left| \mathbf{S}_f \right| + \sum_{f=1}^{N_f} \left(\mathbf{f}_{\mathbf{c}_{\mathbf{P},j}} \right)_f n_j \left| \mathbf{S}_f \right|.$$
(18)

The convective part of the Eulerian flux is computed here by following Piroz-zoli's energy-conserving scheme [17]:

$$\mathbf{f}_{\mathbf{c}_{\mathbf{H},\mathbf{j}}} = \frac{1}{8} \left(\rho^+ + \rho^- \right) \left(u_n^+ + u_n^- \right) \left(\boldsymbol{\varphi}^+ + \boldsymbol{\varphi}^- \right)$$
(19)

where $\varphi = (1, u_1, u_2, u_3, H)^T$ and $u_n = u_j n_j$. The pressure flux is obtained from:

$$\mathbf{f}_{\mathbf{c}_{\mathbf{p},j}} = \frac{1}{2} \left(\mathbf{f}_{\mathbf{c}_{\mathbf{p},j}}^{+} + \mathbf{f}_{\mathbf{c}_{\mathbf{p},j}}^{-} \right) + \mathbf{f}_{\mathbf{c}_{\mathbf{p},j}}^{\mathrm{D}}.$$
 (20)

²²⁵ The diffusive part in the numerical flux of eq. 20, $\mathbf{f_{c_{p,j}}}^{D}$, is activated to increase ²²⁶ the stability of the discretization technique in computations on unstructured ²²⁷ or distorted meshes. In particular, to activate $\mathbf{f_{c_{p,j}}}^{D}$ we rely on a classical shock ²²⁸ sensor, [18]:

229
$$\theta = \max\left(-\frac{\boldsymbol{\nabla} \cdot \mathbf{v}}{\sqrt{(\boldsymbol{\nabla} \cdot \mathbf{v})^2 + |\boldsymbol{\nabla} \wedge \mathbf{v}|^2 + u_0^2/L_0^2}}, 0\right) \qquad \theta \in [0, 1]$$
(21)

where u_0 and L_0 are suitable velocity and length scales [19]. In the cases considered in this paper, as in Modesti and Pirozzoli [20], the artificial diffusion term is designed to be proportional to $\theta_f = (\theta^+ + \theta^-)/2$:

$$\left(\mathbf{f}_{\mathbf{c}_{\mathbf{p},j}}^{\mathrm{D}}\right)_{f} = \alpha \theta_{f} \left(\mathbf{f}_{\mathbf{c}_{\mathbf{p},j}}^{\mathrm{AUSM}}\right)_{f}.$$
(22)

Note that α is a flag controlling the activation of the diffusive pressure flux, while $\mathbf{f_{c_{p,j}}}^{AUSM}$ is obtained using the AUSM⁺–up formula (eqs. (69) to (77) of Liou [21]).

²³⁷ We also wish to mention that the Courant number, Co, is computed in this ²³⁸ work using the following equation:

Co = max
$$\left(\left| \psi_f^+ \right|, \left| \psi_f^- \right| \right) \frac{\delta \Delta t}{|\mathbf{S}_f|}$$
 (23)

240 with:

241

$$\delta = \frac{1}{\max\left(\mathbf{d} \cdot \frac{\mathbf{s}_f}{|\mathbf{s}_f|}, 0.05 \, |\mathbf{d}|\right)},\tag{24}$$

²⁴² d as shown in Fig. 1.

Standard approximation schemes are used for the diffusive fluxes, $\mathbf{f}_{\mathbf{v},j}$. Since discussing such techniques is beyond the scope of this manuscript, we refer readers to the textbook by Ferzinger and Peric [22] for more details.

It is worth noting that flow problems with shock-waves are not considered in the presented numerical methodology. From here on, we refer to the KNPbased solver as caafoam-m1, while caafoam-m2 is used to indicate the solver based on Pirozzoli's scheme.

Lastly, we want to point out that Eikonal equation is solved in its hyperbolic form, eq. 9, using a fully explicit approach. Standard central schemes have been employed for this purpose for structured grids, while upwind techniques have been used for unstructured meshes since in this case the former approach is unstable.

255 3.2 Time integration schemes

258

264

For each FV, the interpolation coefficients obtained from the discretization process are used to form the following system of ODEs:

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} = \mathbf{R}\left(\mathbf{U}\right) \tag{25}$$

where \mathbf{R} is the residual of the space discretization including the convective, diffusive and source terms; and \mathbf{U} is the degrees of freedom (DoFs) vector.

Explicit Runge-Kutta (ERK) schemes were used to solve eq. 25 in the present
work. The ERK Williamson formula [23] was implemented to contain memory
usage. The integration strategy in the k-th RK stage can be summarized as:

$$\Delta \mathbf{U}^{(k)} = A_k \ \Delta \mathbf{U}^{(k-1)} + \Delta \mathbf{t} \ \mathbf{R} \left(\mathbf{U}^{(k-1)} \right),$$

$$\mathbf{U}^{(k)} = \mathbf{U}^{(k-1)} + B_k \ \Delta \mathbf{U}^{(k)}.$$
 (26)

In eq. 26, the A_k and B_k coefficients are functions of the standard Butcher matrix entries, $\mathbf{R}^{(k)}$ is the residual at the k-th intermediate RK stage, and $\mathbf{U}^{(k)}$ is the DoFs vector at the same RK stage. It is important to note that $\mathbf{U}^{(k)}$, $\Delta \mathbf{U}^{(k)}$ and $\mathbf{R}^{(k)}$ must be stored, so only three storage registers for each variable are needed for this kind of scheme. This enables us to obtain a good
performance in large-scale computations too [24].

We considered ERK schemes having an order of accuracy ranging from 2 to 4; the tables of the coefficients A_k and B_k are given below. For the 2nd-order scheme (with 2 stages), named RK 2-2 in the text, we have:

$$\begin{array}{c|c}
A_k & B_k \\
\hline
0 & 1.0 \\
-1.0 & 0.5
\end{array}$$

274

The 3rd-order low-storage ERK scheme (with 4 stages), called RK 3-4 in the paper, is based on the following coefficients proposed by Carpenter and Kennedy [25]:

A_k	B_k
0	8/141
-756391/934407	6627/2000
-36441873/15625000	609375/1085297
-1953125/1085297	198961/526383

278

Lastly, a 4th-order accurate approach (with 5 stages) was also adopted, as
proposed by Kennedy et al. [24], and called RK 4-5 in our work:

A_k	B_k
0	0.1496590219993
-0.4178904745	0.3792103129999
-1.192151694643	0.8229550293869
-1.697784692471	0.6994504559488
-1.514183444257	0.1530572479681

281

282 3.3 Implementation aspects

The solution algorithm is implemented in the OpenFOAM environment [26], which is an open-source library for numerical simulations in continuum mechanics. Thanks to an object-oriented structure, the package is extremely flexible and it allows for outside users to develop complex physical models with relatively little effort.

The basic OpenFOAM classes, *i.e.* scalarField, vectorField and tensorField, 288 have been conceived to mimic the main mathematical tools needed in tra-289 ditional continuum mechanics. Data type can also be specified in the cells 290 or face centers. We also have two different types of tensor-derivative class: 291 finiteVolumeCalculus or fvc, and finiteVolumeMethod or fvm. The for-292 mer performs explicit estimates of tensorial operators, while the latter can 293 return a matrix representation of a given operation. More details about the 294 above-mentioned data types can be found in [26, 27, 28]. 295

In this paper, we only use the basic classes and the fvc-derived class because we opted for an explicit time integration approach. The hyperbolic version ²⁹⁸ of the Eikonal equation was also solved in a fully explicit way using the fvc ²⁹⁹ class.

300 3.4 Parallel performance

To investigate the parallel scalability of caafoam, we considered a widely-used benchmark, i.e. the lid-driven cavity problem of a laminar flow with a low Mach number in a 3D cubic domain [29, 30, 31]. All the boundaries were treated as walls except for the top, which was a moving wall. The strong scaling tests were run on a suite of three evenly-spaced grids with a number of cells N_c amounting to: 320^3 , 240^3 and 160^3 . We also set the Reynolds number at 20, and the Mach number relating to the wall velocity at 0.2.

In our specific case, the simulations were conducted on two different super-308 computers: MARCONI-A2 hosted by CINECA; and MareNostrum hosted 309 by BSC. MARCONI is a NeXtScale cluster consisting of 3600 nodes with 310 a Knights Landing (KNL) 68-core, 1.40 GHz Intel processor. Each node is 311 equipped with 96 GB of RAM and 16 GB of multi-channel dynamic ran-312 dom access memory (MCDRAM). MareNostrum comprises 3456 nodes with 313 two Intel Xeon Platinum 24-core processors of the Skylake (SKL) generation 314 operating at 2.1 GHz for each node. There are 96 GB of RAM available in 315 standard nodes (as used in this work). Both systems are of the Tier-0 type 316 forming part of the PRACE initiative, [32]. 317

The scalability tests discussed below were conducted as part of a preparatory PRACE project aiming to examine the parallel performance of caafoam on massively parallel supercomputers. Access to the machines was limited, so these tests could not be performed using all the solvers considered in this work. Only caafoam-m1 was therefore considered at this stage because it shares the same spatial discretization approach as standard OpenFOAM solvers.

The tests were conducted without any I/O for 100 time-steps to cancel the starting overhead, and using 64 CPU cores for each MARCONI node, while 48 CPU cores were used for each MareNostrum node. The code was built usingIntel compilers and the MPI library version developed by Intel.

Fig. 2 shows the effect of grid size scalability in terms of speed-up and par-328 allel efficiency. It is worth noting that inter-node scalability is good on both 329 systems until the latency due to node communications becomes predominant. 330 It is also very obvious that, on MARCONI, smaller grids have a better par-331 allel performance with fewer cores, while grids with more cells perform better 332 using a larger number of CPU cores. A clearly different trend is apparent on 333 MareNostrum, where performance is almost always super-linear due to cache 334 effects. In this case, smaller grids perform better than larger ones until com-335 munications issues override the parallel effects. A super-linear behavior is only 336 achieved on MARCONI up to 2048 CPU cores, using the finest grid, on which 337 we obtain a good parallel performance up to 8192 CPU cores. A good effi-338 ciency was achieved on MARCONI up to $4 \cdot 10^3$ cells for each core, while on 339 MareNostrum we obtained an efficiency of about 88 % with 2250 cells per 340 core. 341

As concerns the above results, it is important to note that adopting an explicit time integration approach is particularly appealing from the parallel efficiency standpoint. Appropriately selecting the scheme coefficients also enables us to obtain good stability limits, as shown in Section 4.1.1. These are the reasons why we consider caafoam an appealing tool for massively parallel aeroacoustic simulations.

348 4 Results

Several literature benchmark problems were considered to test the reliability of the caafoam solver. We considered the far-field aerodynamic sound generated by bluff bodies in a flow with a uniform inlet velocity, in various arrangements, at low Mach numbers. The cases of a single circular cylinder and of two square cylinders placed side by side, as well as in a tandem configuration, were analyzed to test the capabilities of our approach. Then a numerical study
was conducted on the effect of the wall's thermal boundary conditions on the
aeroacoustic field by addressing the sound generated by the flow over isolated
square and circular cylinders.

In all the above-mentioned cases, the Mach number of the undisturbed flow was $M_{\infty} = 0.2$, $\gamma = 1.4$, and the Prandtl number, Pr, was 0.75. We present the results below in terms of standard parameters relating to fluid dynamic and acoustic fields, i.e. (i) drag and lift coefficients; (ii) the Strouhal number; (iii) fluctuations in pressure and its root mean square; and (iv) dilatation rate field. The dimensionless drag and lift coefficients are given by eq. 27:

$$C_D = \frac{2D'}{\rho u_{\infty}^2 A_{ref}}, \quad C_L = \frac{2L'}{\rho u_{\infty}^2 A_{ref}}.$$
 (27)

Standard statistics are used to analyze force coefficients behavior: the mean drag coefficient $\langle C_D \rangle$, the root mean square of the lift coefficient $C_{L,rms}$, and the amplitudes of oscillation of the force coefficients ($\Delta C_D = (C_{D,max} - C_{D,min})/2$, and $\Delta C_L = (C_{L,max} - C_{L,min})/2$). The Strouhal number is defined as:

375

$$St = \frac{fL_{ref}}{u_{\infty}} \tag{28}$$

where f is the vortex-shedding frequency found from spectral analysis of the time history of the fluctuating lift coefficient, and L_{ref} is the reference length. The acoustic results are presented below in terms of dimensionless fluctuating pressure, defined as:

$$p' = \frac{p - \langle p \rangle}{\rho_{\infty} c_{\infty}^2} \tag{29}$$

where $\langle p \rangle$ is the average pressure field and c_{∞} is the speed of sound of the undisturbed flow. Polar plots containing the root mean square of p' are shown to elucidate the sound features in the far field. For the purpose of a comparison with the literature, the acoustic statistics were sampled over a dimensionless time $u_{\infty}T/D = 100$. Unless stated otherwise, the plots are built at r/D = 75. The dilatation rate field, $\partial u_j/\partial x_j$, is also used to visualize the acoustic wave because, taking the mass conservation equation into account, it equates to the negative rate of change of the density which is directly linked to p'.

Finally, the acoustic power output, defined as the acoustic intensity flux through a closed circle surrounding the source and having a radius r', is examined to estimate the wall heating effects on the sound produced. The analytical expression of the acoustic power is as follows:

$$W = \int_0^{2\pi} I_a \left(r = r', \theta \right) R d\theta \tag{30}$$

where $I_a = (p'_{rms})^2 / \rho c$ accounts for the mean acoustic intensity in the far-field region. The sound power level is obtained as:

$$L_w = 10 \log_{10} \frac{W}{W_0}$$
(31)

where W_0 is the reference acoustic power.

All the solutions were obtained on distributed-memory parallel machines: the 393 computations requiring a lower load were run on a Linux Cluster, with 16 Intel 394 Xeon E5-2603v3-based nodes, for a total of 192 CPU cores operating at 1.6 395 GHz. Larger cases were run on a MARCONI-A2 system. Intel's libhbm library, 396 which can be downloaded from the OpenFOAM-dev-Intel branch on Github 397 (https://github.com/OpenFOAM/OpenFOAM-Intel/tree/master/libhbm), was 398 used to enable access to the MCDRAM. Adopting libhbm enabled us to speed 399 up the computations by up to 20%. 400

401 4.1 Validation cases

388

402 4.1.1 Circular cylinder

The first test case in this work concerns the sound generated by the Karman vortex street that is shed behind a circular cylinder. The Reynolds number based on the cylinder's diameter is Re = 150. The problem had already been considered in the context of sound generation computation [33, 34, 35, 36], so
it is an appropriate benchmark for caafoam.

Two different suites of computational meshes were generated to test the perfor-408 mance of caafoam. A first group included three fully-structured O-type grids. 409 The coarser structured grid, named G1, was created with $N_c = 3.5 \cdot 10^5 (500 \times$ 410 700); the G2 grid was generated by starting from G1 and increasing the num-411 ber of cells in the radial direction, $N_c = 5.25 \cdot 10^5 (750 \times 700)$. The last grid, 412 G3, was the result of a further refinement in the radial direction: $N_c = 7 \cdot 10^5$ 413 (1000×700) . It is important to remark that the G series grids have a number 414 of cells per wavelength equal to about: 90 for G1, 135 for G2 and 180 for G3. 415 Note also that the previous data are compatible with recent literature refer-416 ences [36, 37, 38]. Our second set of computational meshes consisted of two 417 fully-unstructured (triangular cells) grids: the U2 grid had about $2 \cdot 10^6$ cells 418 and was obtained by refining a starting grid, named U1 with $N_c \simeq 5.2 \cdot 10^5$, 419 in order to have a wavelength resolution comparable to G2 grid. In all the 420 above cases, the far-field boundaries were placed at 150 times the cylinder's 421 diameter, D, and the height of the first cell next to the wall, y_c , was set at 422 $y_c/D = 5 \cdot 10^{-3}$. The sponge's strength was set at 40 dB. The different space 423 discretized domains were tested using both versions of caafoam, i.e. m1 and 424 m2. 425

An instantaneous representation of the pressure wave generated by vortex shedding, computed with our low-dissipation approach, is shown in Fig. 3. It contains the positive and negative pressure pulses, alternately produced from the upper and lower sides of the cylinder, as also noted by Inoue and Hatakeyama, [34].

Fig. 4 shows the polar plots of the root mean square of the fluctuating pressure, p'_{rms} , obtained using the RK 4-5 scheme and the maximum allowable Co number. The nature of the sound field clearly emerges, also confirming that the lift dipole dominates. Fig. 4(a) clearly shows that good reconstruction of the acoustic far field can be obtained with the G2 grid. In fact, solutions G2

and G3 are almost indistinguishable, while some little wiggles appear for in the 436 case of G1. It is important to note that caafoam-m1 and caafoam-m2 (without 437 the dissipative term on the pressure flux, *i.e* $\alpha = 0$ produce very similar re-438 sults on the structured grids. On the other hand, caafoam-m1 proved unstable 439 on our unstructured grids without any limiters on the interpolation schemes 440 for the DoFs, which in turn cause acoustic wave depletion. Only caafoam-m2 441 with $\alpha = 1$ proved capable of directly simulating the acoustic field on the U1 442 and U2 grids (see Fig. 4(b)). The main drawback of adopting unstructured 443 grids, however, lies in the dramatic increase in the number of cells needed to 444 obtain acceptable predictions. Our investigations were consequently limited to 445 structured meshes from this point on. 446

Fig. 5 is worthy of careful attention because it shows the comparison (per-447 formed on the G2 grid) between our approach and the results obtained with 448 rhoCentralFoam. The solver is density-based and available in the official 449 OpenFOAM release. It adopts the KNP scheme for the space discretization of 450 the convective terms [16]. In this particular case, rhoCentralFoam was submit-451 ted to the non-reflective boundary treatment described in Section 2.1. Fig. 5 452 shows that rhoCentralFoam is unable to properly reconstruct the acoustic 453 field. This is due to the significant amount of numerical dissipation intro-454 duced by the solver, as also noted by Modesti and Pirozzoli [20] in a different 455 context. We might also add that the "backward" scheme, available in the offi-456 cial OpenFOAM releases, was used in rhoCentralFoam for time integration. 457 The RK-based approaches proposed in this work show a very good agree-458 ment with the reference data in both caafoam-m1 and caafoam-m2 modes (see 459 Fig. 4). They also show a directivity of 83° , which differs from Inoue and 460 Hatakeyama, who found 78.5°, by 5.7%. We can therefore conclude that, on 461 structured grids, the space discretization needed to handle Eulerian numerical 462 fluxes is not the crucial issue. Our results demonstrate that, in the FV frame-463 work, the solution strategy of space discretized equations has a central role 464 in the correct prediction of acoustic waves. For the sake of completeness, we 465

must add that applying rhoCentralFoam to unstructured grids suffers from 466 the same problems as those described for caafoam-m1, which also use the KNP 467 approach. In our computational experience, we found that a Co_{max} of about 1 468 can be used when the RK 4-5 technique was adopted. The RK 3-4 scheme only 469 proved stable for $Co_{max} \simeq 0.6$, whereas for RK 2-2 the maximum allowable 470 Courant number was around 0.4. Fig. 5 suggests that the RK 2-2 approach is 471 the best choice for solving the governing equations because, in both m1 and 472 m2 modes, it enables us to obtain results comparable with the RK 3-4 and 473 RK 4-5 schemes using only 2 stages. We have to emphasize, however, that the 474 RK 2-2 and RK 4-5 schemes are less costly because they have the same ratio 475 between the number of computational operations and the stability limits. In 476 the following cases, we preferred to adopt the RK 4-5 technique because it 477 provided slightly better results than the RK 2-2 method. As shown in Fig. 6, 478 the increase in the size of the Δt does not significantly affect the accuracy of 479 the solution for either of the schemes for approximating the convective terms 480 considered in this paper. 481

Finally, we wish to confirm that a non-reflective boundary treatment is indispensable for DNS cases. Sponge-layer-free numerical solutions produce completely nonphysical results (see Fig. 7). A sponge strength of 40 dB suffices, as also noted by Mani [13], to properly suppress spurious wave reflections near the boundary field. The sponge layer thickness was computed using the criterion discussed in Section 2.1.

Table 1 and Table 2 show the aerodynamic parameters regarding the effect of 488 the time-step's size, including the rhoCentralFoam solutions. The maximum 489 dimensionless time-step size, $u_{\infty}\Delta t/D$, was chosen in order to overcome the 490 stability limit of the scheme considered. For rhoCentralFoam, Co_{max} has to be 491 less than 0.2 to avoid the computation blowing up. For the sake of compact-492 ness, the above-mentioned results only refer to the G2 grid, and they almost 493 converge. The force coefficients established with caafoam are very consistent 494 with the results reported by Inoue and Hatakeyama [34], and by Muller [33] 495

high-order finite difference data (see Table 3). The Strouhal number was also
computed, obtaining St = 0.182 for all the cases considered. Here again, our
results are very consistent with the main references in the literature. Compared with caafoam, the rhoCentralFoam solver slightly overestimates the
amplitudes of the aerodynamic coefficients, but it has a good overall fit with
the data in the literature.

502 4.1.2 Square cylinders arranged side by side: L/D = 3

In this subsection we discuss the results concerning the flow field and sound 503 generation around two square cylinders placed side by side, as shown in Fig. 8. 504 The ratio L/D was set at 3, where L is the spacing between the centers of 505 the two cylinders and D is the diameter. The Reynolds number, based on a 506 single cylinder's diameter, is Re = 150. Depending on the initial condition, 507 a bifurcation of the wake patterns appears for this flow configuration, as for 508 circular cylinders [39]. Different sound patterns are generated in response to 509 this phenomenon [40]. In this work, a symmetrical initial field (with respect to 510 the y = 0 plane) was imposed by two vortices, one moving clockwise and the 511 other counterclockwise, behind the upper and lower cylinders, respectively. 512 The resulting flow field is described as in-phase because it exhibits synchro-513 nized lift coefficients (Fig. 9(b)). Fully-structured orthogonal computational 514 grids were used, adopting a sponge layer with a strength of 40 dB. The grid 515 cells were clustered near the cylinder walls, whereas the far field was placed 516 at 200 D from the midpoint of the two cylinders (see Fig. 8). N_c was set at 517 $1.11 \cdot 10^6$. It should be noted that we had to extend the domain due to the 518 lower frequency of vortices shed behind the square cylinders than behind the 519 single circular one. For this reason, L_{sp} was increased to keep the dimension-520 less extent of the sponge layer, $L_{sp}f/c_{\infty}$, at 0.5. The inflow/outflow conditions 521 were consequently set at 200 D to avoid interference phenomena between the 522 acoustic far field and the layer. A finer version of the grid was also generated: 523

it has a number of cells equating to half that of the previous grid, with a total number of $4.44 \cdot 10^6$, and the height of the dimensionless first cell bordering on the walls is 10^{-2} . Note that the finest grid guarantees about 180 cells per wavelength. Time integration was performed using the RK 4-5 scheme and the size of the dimensionless time step was set at $1.8 \cdot 10^{-3}$. This enabled us to obtain a maximum Courant number of around 1 for the finer grid. The larger case was run on the MARCONI-A2 system using 256 CPU cores.

The main aims of this benchmark are to further validate caafoam, and also to investigate the role of the solution strategy involving space-discretized equations in the context of the structured grids. We consequently limit our efforts to the m1 version of our code because it uses the same space discretization approach as rhoCentralFoam, and it is equivalent to m2 in terms of the results on structured grids.

Table 4 shows the aerodynamic parameters predicted from the above-mentioned 537 computations. An overall good agreement emerged between our data and those 538 in the literature. We might also add that it is hard to say whether the intrinsi-539 cally dissipative nature of rhoCentralFoam could affect the forces predicted. 540 Finally, Fig. 10 shows the acoustic results. The overall results show a good 541 agreement with the findings of Inoue et al. [40], but our grid refinement clearly 542 improved the agreement between the data presented here and those in the lit-543 erature. Fig. 10(a) shows the p'_{rms} polar plot, which is very similar to the 544 case of the single circular cylinder: a directivity of 80.2° was obtained. It is 545 important to note that the sound wave is always symmetrical to the y = 0546 plane, and of a similar nature to the longitudinal quadrupole, as discussed in 547 Blake [41]. Once again, the non-reflective rhoCentralFoam version does not 548 properly reconstruct the acoustic far field, as shown in Fig. 10. 549

This confirms that, here too, the space discretization schemes adopted for the governing equations are not the main factor responsible for correctly predicting acoustic waves.

With the same aims as for the side-by-side arrangement, we also considered 554 the flow and sound generation around two square cylinders in a tandem config-555 uration with L/D = 2, where L and D have the meaning expressed in Fig. 11. 556 The computational domain was generated to place the far field 200 D away 557 from the origin of the Cartesian frame in Fig. 11. Quadrilateral orthogonal 558 cells were used to discretize the flow domain. The total number of cells, N_c , 559 was about $4.2 \cdot 10^6$, and a grid refinement was performed near the walls of 560 the cylinders adopting $y_c/D = 10^{-2}$. This grid allow to have about 190 cells 561 per wavelength for the specific configuration. As for the side-by-side config-562 uration, we tested a coarser grid with a quarter of the N_c of the finer one. 563 The caafoam-m1 solutions are based on the RK 4-5 time integration scheme to 564 obtain a maximum allowable Courant number of around 1. So $u_{\infty}\Delta t/D$ was 565 set at $9 \cdot 10^{-3}$ for the finer grid. Acoustic wave reflections at the far boundaries 566 were removed using a configuration derived from the previous test cases; the 567 sponge layer's strength was 40 dB, while its dimensionless thickness was 0.5 568 to limit the computational resources required. Finer grid computations were 569 run using 256 CPU-cores MARCONI-A2 HPC system. 570

Table 5 shows the aerodynamic parameters for the square cylinders in tan-571 dem. The picture is similar to the one seen for the side-by-side cylinders. The 572 features of the sound field generated by the interaction of the flow and the two 573 cylinders are shown in Fig. 12. The p'_{rms} plot in Fig. 12(a) refers to a circle 574 having a r/D of 80. caafoam-m1 results, achieved with the finer grid, are con-575 sistent with the reference data in the literature [42], and reveal a directivity 576 of 71.2° . Lastly, we wish to add that, for this test case too, the non-reflective 577 **rhoCentralFoam** is inappropriate for far-field sound computation. Fig. 12(a) 578 clearly shows that, in the far zone of the acoustic field, rhoCentralFoam is 579 not consistent with the data reported in [42]. 580

Two different configurations were considered to analyze the effect of the ther-582 mal boundary conditions at the wall on the acoustic field generated by the 583 laminar flows around bluff bodies: a single circular cylinder at Re = 150, and 584 a single square cylinder at the same Re number. In both problems, the base-585 line configuration involved an adiabatic wall; then cases having $T_w = 2T_\infty$ 586 and $T_w = 3T_\infty$ were also investigated. $M_\infty = 0.2$ was used to conduct this 587 assessment. Given the results presented in the previous sections, the following 588 data were based on caafoam-m1. 589

The first case we mention, represented in Fig. 13, is the sound radiated by 590 the Karman vortex street shed behind a square cylinder. A fully-structured 591 orthogonal grid was used: the grid cells were clustered near the cylinder walls 592 using a dimensionless first cell height, y_c/D , of $5 \cdot 10^{-3}$, and far-field boundaries 593 placed at a distance of 200 D from the center of the cylinder. The resulting 594 computational mesh had a total number of cells, N_c , amounting to $4.4 \cdot 10^6$ with 595 about 170 cells per wavelength. The polar plot containing the p'_{rms} is shown 596 in Fig. 16(a). The data were collected over a circumference built around the 597 square cylinder having a dimensionless radius r/D = 75, as in Inoue et al. [42]. 598 Our approach clearly ensures a good reconstruction of the acoustic far field. It 599 is important to note that, for the flow regimes considered, the acoustic field is 600 generated by periodical vortical structures shedding. This phenomenon causes 601 a pressure fluctuation on the cylinder's surfaces, leading to the generation an 602 unsteady lift/downforce. The drag is influenced by the Karman vortex street 603 as well, showing a downstream/upstream pulsation. These perturbations have 604 a sound quadrupole nature, but the dominance of the lift fluctuation yields a 605 typical dipolar acoustic field [43]. 606

Note that, due to thermal effects, in order to estimate the changes in the acoustic field we present our data on a circle having r = 40 D as this prevents an excessive sound wave decay in the far field. This condition enabled us to set

the extent of the computational domain at r = 150 D, reducing the number of 610 cells to: $N_c \simeq 3 \cdot 10^6$. Fig. 14 shows that the rise in wall temperature increases 611 $\langle C_D \rangle$ and reduces $C_{L,rms}$. Fig. 15 shows that the force coefficient pulsations, 612 ΔC_D and ΔC_L , are reduced as a result of the increase in wall temperature. 613 These results are in agreement with the reports from Lecordier et al. [8, 9], 614 who experimentally found vortex shedding dumping behind a heated circu-615 lar cylinder. Similar effects were also found on heated airfoils operating at low 616 Re, [44, 45, 46], which revealed a higher drag force and lower lift force in steady 617 conditions. Looking at the results in Fig. 15, it is easy to see that the sound 618 sources, *i.e.* ΔC_D and ΔC_L , are damped, producing a far-field sound abate-619 ment at higher wall temperatures. It is worth noting that this phenomenon 620 is not limited to a specific Re but holds throughout the range of 90-150, as 621 shown in the figures from Fig. 16 to Fig. 19. The radiated sound decay is also 622 less significant for higher Re numbers, as shown in Fig. 20(b). In particular, 623 at Re = 90 the maximum sound power level decay $(T_w = 3T_\infty)$ is slightly less 624 than 5 dB, while at Re = 150 it is ~ 3 dB, which is still significant. The St 625 number is reduced by wall heating as well, as shown in Fig. 20(a), consistently 626 with the findings of Lecordier et al.. 627

The second case considered in this context is the sound radiated by the Karman vortex street that is shed behind a circular cylinder. The fully-structured G2 grid was used for this analysis. All the numerical settings mentioned in Section 4.1.1 were confirmed here to investigate the effects of wall heating on the radiated sound. As for the square cylinder, we present the p'_{rms} data on a circle having r = 40 D.

In this case, increasing the wall temperature produced an evident reduction in $C_{L,rms}$, while $\langle C_D \rangle$ was increased up to Re = 130. Fig. 21 clearly shows, however, that the thermal boundary conditions at the wall have a more significant effect on the lift coefficient in this flow configuration, whereas the effect on $\langle C_D \rangle$ is almost negligible. As for the square cylinder, the force coefficient fluctuations are dumped.

In short, the aeroacoustic sound emitted in the far-field region is lower when 640 the wall temperature is higher, as shown in Fig. 23 to Fig. 26. It is also im-641 portant to note that the sound decay is less significant at higher Re numbers 642 in this configuration, as confirmed by Fig. 27(b). It is also worth noting that 643 overall L_w abatement is greater for the circular cylinder than for the square 644 one. In fact, we obtained $\Delta L_w \simeq 8 \text{dB}$ at Re = 90, and ~ 5dB at Re = 150. 645 Lastly, the St number shows the same behavior vis-à-vis Re and wall temper-646 ature as for the square cylinder. 647

At the time of writing this paper, there were no papers available in the open literature dealing with the reduction of emitted aeroacoustic sound based on wall heating. The above-mentioned phenomenon was analyzed on two completely different geometries, showing that it is not limited to a particular flow configuration.

653 5 Conclusions

This paper addresses the development and application of an open-source solver 654 for compressible mass, momentum and energy equations, named caafoam, 655 which is able to capture a wide range of flow phenomena. Particular atten-656 tion was devoted to computing aeroacoustic sound. Our solver was devel-657 oped within the FV OpenFOAM library and it adopts explicit low-storage 658 Runge-Kutta schemes for time integration. KNP and Pirozzoli energy con-659 serving schemes were used to handle Eulerian numerical fluxes, while stan-660 dard central schemes were considered for diffusive terms. Only the Pirozzoli 661 schemes proved capable of predicting acoustic waves on fully unstructured 662 computational grids, while the two different approaches performed equally 663 well on structured grids. An appropriate non-reflective boundary treatment 664 was achieved using an artificial sponge layer because it is simple to code, ro-665 bust, and not stiff; and it proved flexible in handling complex geometries. The 666 solver also showed a very good parallel performance on two completely differ-667

ent architectures, making it suitable for use in massively parallel aeroacoustic computations.

A broad range of far-field aeroacoustic sound configurations, emitted from 670 bluff-bodies in a flow with uniform velocity inlet, was investigated for vali-671 dation purposes. In all the benchmarks considered, caafoam performed well 672 in predicting the sound produced by the flow-body interaction. We found 673 rhoCentralFoam unable to capture acoustic wave propagation phenomena 674 correctly, even though we had introduced a proper non-reflective boundary 675 treatment. On the other hand, the caafoam-m1 version can produce a direct 676 solution of aeroacoustic fields. This goes to show that the inviscid numerical 677 flux is not the key ingredient on structured grids; the solution algorithm is the 678 primary issue to address. 679

Another novelty of this paper concerns our assessment of the impact of ther-680 mal boundary conditions at the wall on the sound produced by the interaction 681 of a bluff body with a uniform laminar flow. Two different cases were consid-682 ered, with square and circular cylinders. In both cases, we found that heating 683 the wall reduces the vortex shedding developing in the wake region, as noted 684 experimentally by Lecordier et al. [8]. This is of considerable interest in aeroa-685 coustics because the pulsations of the lift and drag forces for these objects 686 are directly related to the aerodynamically-produced sound. In fact, reducing 687 them by heating the wall in turn reduces the production of acoustic pertur-688 bations. In other words, increasing the wall temperature reduces the sound 689 power level. This finding has important practical implications since it can be 690 considered as a method for actively controlling aeroacoustic sound. 691

692 6 Acknowledgements

⁶⁹³ We acknowledge the CINECA Award N. HP10CG4PUI YEAR 2018 under ⁶⁹⁴ the ISCRA initiative, for the availability of high performance computing re-⁶⁹⁵ sources and support. We acknowledge the type-A preparatory PRACE project ⁶⁹⁶ 2010PA4840 YEAR 2019 for the availability of high performance computing ⁶⁹⁷ resources and support.

698 References

- [1] S. K. Lele and J.W. Joseph. A second golden age of aeroacoustics? *Philo-*sophical Transactions of the Royal Society of London A: Mathematical, *Physical and Engineering Sciences*, 372(2022), 2014.
- T. Tim Colonius and S.K. Lele. Computational aeroacoustics: progress on nonlinear problems of sound generation. *Progress in Aerospace Sciences*, 40(6):345 - 416, 2004.
- [3] C.K.W. Tam. Computational aeroacoustics: An overview of computational challenges and applications. *International Journal of Computa- tional Fluid Dynamics*, 18(6):547–567, 2004.
- P.J. Morris, L.N. Long, T.E. Scheidegger, and S. Boluriaan. Simulations
 of supersonic jet noise. *International Journal of Aeroacoustics*, 1(1):17–41, 2002.
- M. Lorteau, F. Clero, and F. Vuillot. Analysis of noise radiation mechanisms in hot subsonic jet from a validated les solution. *Physics of Fluids*, 27(17), 2015.
- ⁷¹⁴ [6] H.M. Frank and C.D. Munz. Direct aeroacoustic simulation of acous⁷¹⁵ tic feedback phenomena on a side-view mirror. Journal of Sound and
 ⁷¹⁶ Vibration, 371:132 149, 2016.
- ⁷¹⁷ [7] B. Cockburn, G.E. Karniadakis, and C.W. Shu. Discontinuous Galerkin
 ⁷¹⁸ Methods Theory, Computations and Applications. Springer–Verlag,
 ⁷¹⁹ Berlin, 2000.
- J.C. Lecordier, L. Hamma, and P. Paranthoen. The control of vortex
 shedding behind heated circular cylinders at low reynolds numbers. *Experiments in Fluids*, 10(4):224–229, 1991.
- ⁷²³ [9] J.-C. Lecordier, L.W.B. Browne, S. Le Masson, F. Dumouchel, and

- P. Paranthoen. Control of vortex shedding by thermal effect at low
 reynolds numbers. *Experimental Thermal and Fluid Science*, 21(4):227–
 237, 2000.
- [10] M. Israeli and S.A. Orszag. Approximation of radiation boundary conditions. Journal of Computational Physics, 41:115–135, 1981.
- [11] D.J. Bodony. Analysis of sponge zone for computational fluid mechanics.
 Journal of Computational Physics, 212:681–702, 2006.
- [12] T. Ikeda, T. Takashi Atobe, and S. Takagi. Direct simulations of trailing–
 edge noise generation from two-dimensional airfoils at low Reynolds numbers. Journal of Sound and Vibration, 331(3):556 574, 2012.
- [13] A. Mani. Analysis and optimization of numerical sponge layers as a nonreflective boundary treatment. *Journal of Computational Physics*, 231(2):704–716, 2012.
- [14] G. Kreiss, B. Krank, and G. Efraimsson. Analysis of stretched grids
 as buffer zones in simulations of wave propagation. *Applied Numerical Mathematics*, 107:1 17, 2016.
- [15] A. Kurganov, S. Noelle, and G. Petrova. Semidiscrete central-upwind
 schemes for hyperbolic conservation laws and Hamilton-Jacobi equations. *SIAM Journal on Scientific Computing*, 23:707–740, 2001.
- [16] C.J. Greenshields, H.G. Weller, L. Gasparini, and J.M. Reese. Implementation of semi-discrete, non-staggered central schemes in a colocated,
 polyhedral, finite volume framework, for high-speed viscous flows. *Inter- national Journal for Numerical Methods in Fluids*, 63(1):1–21, 2010.
- [17] S. Pirozzoli. Generalized conservative approximations of split convective derivative operators. *Journal of Computational Physics*, 229(19):7180 7190, 2010.
- [18] F. Ducros, V. Ferrand, F. Nicoud, C. Weber, D. Darracq, C. Gacherieu,
 and T. Poinsot. Large–Eddy Simulation of the Shock/Turbulence Interaction. Journal of Computational Physics, 152(2):517 549, 1999.
- ⁷⁵³ [19] S. Pirozzoli. Numerical methods for high-speed flows. Annual Review of

- [20] D. Modesti and S. Pirozzoli. A low-dissipative solver for turbulent compressible flows on unstructured meshes, with OpenFOAM implementation. Computers & Fluids, 152:14 23, 2017.
- M. S. Liou. A sequel to AUSM, Part II: AUSM+-up for all speeds. Journal
 of Computational Physics, 214(1):137 170, 2006.
- [22] J.H. Ferziger and M. Peric. Computational Methods for Fluid Dynamics.
 Springer, 1999.
- [23] J.H Williamson. Low-storage Runge-Kutta schemes. Journal of Com putational Physics, 35(1):48 56, 1980.
- [24] C.A. Kennedy, M.H. Carpenter, and R.M. Lewis. Low-storage, explicit
 Runge-Kutta schemes for the compressible Navier-Stokes equations. Ap-
- $_{766}$ plied Numerical Mathematics, 35(3):177 219, 2000.
- ⁷⁶⁷ [25] M.H. Carpenter and C.A. Kennedy. Third order 2N-storage Runge⁷⁶⁸ Kutta schemes with error control. Technical Memorandum 109111,
 ⁷⁶⁹ NASA, 1994.
- ⁷⁷⁰ [26] H.G. Weller, G. Tabor, H. Jasak, and C. Fureby. A tensorial approach
- to computational continuum mechanics using object-oriented techniques.
 Computational Physics, 12(6):620–631, 1998.
- [27] V. Vuorinen, J.-P. Keskinen, C. Duwig, and B.J. Boersma. On the implementation of low-dissipative Runge-Kutta projection methods for time
 dependent flows using OpenFOAM. *Computers & Fluids*, 93:153 163,
 2014.
- 777 [28] OpenCFD Ltd. OpenFOAM programmer's guide, 2016.
 778 www.openfoam.com.
- [29] G. Axtmann and U. Rist. Scalability of OpenFOAM with Large Eddy
 Simulation and DNS on HPC Systems. In *High Performance Computing in Science and Engineering*, Germany, 2016.
- ⁷⁸² [30] M. Culpo. Current Bottlenecks in the Scalability of OpenFOAM on
 ⁷⁸³ Massively Parallel Clusters, 2011. PRACE white paper, available on

⁷⁵⁴ Fluid Mechanics, 43:163–194, 2011.

784 www.prace-ri.eu.

- [31] V. D'Alessandro, S. Montelpare, and R. Ricci. Detached–eddy simulations
 of the flow over a cylinder at Re = 3900 using OpenFOAM. Computers *& Fluids*, 136:152–156, 2016.
- ⁷⁸⁸ [32] www.prace-ri.eu. Partenership for Advanced Computing in Europe.
- [33] B. Muller. High order numerical simulation of aeolian tones. Computers
 and Fluids, 37:450-462, 2008.
- [34] O. Inoue and N. Hatakeyama. Sound generation by a two-dimensional circular cylinder in a uniform flow. *Journal of Fluid Mechanics*, 471:285–314, 2002.
- [35] M. Dumbser. Arbitrary high order PNPM schemes on unstructured
 meshes for the compressible Navier–Stokes equations. Computers & Flu-*ids*, 39(1):60–76, 2010.
- ⁷⁹⁷ [36] N. Ganta, B. Mahato, and Y.G. Bhumkar. Analysis of sound generation
 ⁷⁹⁸ by flow past a circular cylinder performing rotary oscillations using direct
 ⁷⁹⁹ simulation approach. *Physics of Fluids*, 31(2), 2019.
- [37] N. Ganta, B. Mahato, and Y.G. Bhumkar. Modulation of sound waves
 for flow past a rotary oscillating cylinder in a non-synchronous region. *Physics of Fluids*, 31(9), 2019.
- [38] Ruixian Ma, Zhansheng Liu, Guanghui Zhang, Con J. Doolan, and
 Danielle J. Moreau. Control of Aeolian tones from a circular cylinder
 using forced oscillation. Aerospace Science and Technology, 94:105370,
 2019.
- [39] S. Kang. Characteristics of flow over two circular cylinders in tandem
 and side-by-side arrangment. *Physics of Fluids*, 15, 2003.
- [40] O. Inoue, W. Iwakami, and N. Hatakeyama. Aeolian tones radiated from
 flow past two square cylinders in a side-by-side arrangement. *Physics of Fluids*, 18, 2006.
- [41] W.K. Blake. Mechanics of Flow induced Sound and Vibration. Academic,
 New York, 1986.

32

- [42] O. Inoue, M. Mori, and N. Hatakeyama. Aeolian tones radiated from flow
 past two square cylinders in tandem. *Physics of Fluids*, 18(4), 2006.
- [43] W. Blake. Mechanics of flow-induced sound and vibrations. Elsevier, New
 York, 2017.
- [44] Kim, J., and Koratkar, N., and Rusak, Z. Small-Scale Airfoil Aerodynamic Efficiency Improvement by Surface Temperature and Heat Transfer. AIAA Journal, 41:2105–2112, 2012.
- [45] Bekka, N. and Sellam, M. and Chpoun, A. Numerical Study of Heat
 Transfer Around the Small Scale Airfoil Using Various Turbulence Models. Numerical Heat Transfer, Part A: Applications, 56:946–969, 2009.
- [46] Hinz, F.D., and Alighanbari, H., and Breitsamter, C. Influence of heat
 transfer on the aerodynamic performance of a plunging and pitching
 NACA0012 airfoil at low Reynolds numbers. *Journal of Fluids and Struc*-*tures*, 37:88–99, 2013.
- [47] C.H.K. Williamson. Vortex dynamics in the cylinder wake. Annual Review of Fluid Mechanics, 28:477–539, 1996.



Figure 1. The computational cells.



Figure 2. Parallel performance.



Figure 3. Sound wave generated by the flow past a circular cylinder at Re = 150.



Figure 4. Flow past a circular cylinder at $\mathrm{Re}=150.$ Grids effect.



Figure 5. Flow past a circular cylinder at Re = 150. G2 grid. RK scheme effect; ${\rm Co}_{max}\simeq 0.2.$



Figure 6. Flow past a circular cylinder at Re = 150. G2 grid. Time-step size effect.



Figure 7. Flow past a circular cylinder at $\mathrm{Re}=150.~\mathrm{G2}$ grid. Sponge layer strength impact.



Figure 8. Cylinders arranged side by side.



(a) Dimensionless vorticity field

(b) Force coefficients time history

Figure 9. Square cylinders side by side at Re = 150, $M_{\infty} = 0.2$, L/D = 3. Finer grid results.



Figure 10. Square cylinders side by side at Re = 150, $M_{\infty} = 0.2$, L/D = 3.



Figure 11. Square cylinders in tandem configuration.



Figure 12. Square cylinders in tandem at Re = 150, $M_{\infty} = 0.2$, L/D = 2.



Figure 13. Wall temperature effect, square cylinder Re = 150. Dimensionless $\partial u_j/\partial x_j.$



Figure 14. Wall temperature effect, square cylinders. Force coefficients.



Figure 15. Wall temperature effect, square cylinders. Force coefficients fluctuations.



Figure 16. Wall temperature effect, square cylinder at Re = 150.



Figure 17. Wall temperature effect, square cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 18. Wall temperature effect, square cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 19. Wall temperature effect, square cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 20. Wall temperature effect, square cylinder.



Figure 21. Wall temperature effect, circular cylinder. Force coefficients.



Figure 22. Wall temperature effect, circular cylinder. Force coefficients fluctuations.



Figure 23. Wall temperature effect, circular cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 24. Wall temperature effect, circular cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 25. Wall temperature effect, circular cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 26. Wall temperature effect, circular cylinder. $p_{rms}^\prime,\,r/D=40.$



Figure 27. Wall temperature effect, circular cylinder.

Cylinder at $Re = 150$, $M_{\infty} = 0.2$, G2–grid results. Californian					
Case	$u_{\infty}\Delta t/D$	$\langle C_D \rangle$	$\Delta C_D \cdot 10^2$	ΔC_L	St
RK 2–2 (Co _{max} $\simeq 0.2$)	$2 \cdot 10^{-4}$	1.3326	2.580	0.5203	0.182
RK 2–2 (Co _{max} $\simeq 0.4$)	$4\cdot 10^{-4}$	1.3325	2.560	0.5200	0.182
RK 3–4 (Co _{max} $\simeq 0.2$)	$2\cdot 10^{-4}$	1.3329	2.570	0.5203	0.182
RK 3–4 (Co _{max} $\simeq 0.4$)	$4 \cdot 10^{-4}$	1.3329	2.575	0.5201	0.182
RK 3–4 (Co _{max} $\simeq 0.6$)	$6 \cdot 10^{-4}$	1.3325	2.580	0.5199	0.182
RK 4–5 (Co _{max} $\simeq 0.2$)	$2 \cdot 10^{-4}$	1.3329	2.580	0.5203	0.182
RK 4–5 (Co _{max} $\simeq 0.4$)	$4 \cdot 10^{-4}$	1.3328	2.575	0.5201	0.182
RK 4–5 (Co _{max} $\simeq 1.0$)	$8\cdot 10^{-4}$	1.3325	2.570	0.5199	0.182
rhoCentralFoam ($\mathrm{Co}_{max}\simeq 0.2$)	$2\cdot 10^{-4}$	1.3347	2.580	0.5215	0.182

Table 1 Cylinder at Re = 150, $M_{\infty} = 0.2$, G2-grid results. caafoam-m1

Cylinder at $Re = 150$, $M_{\infty} = 0.2$, G2–grid results. California					
Case	$u_{\infty}\Delta t/D$	$\langle C_D \rangle$	$\Delta C_D \cdot 10^2$	ΔC_L	St
RK 2–2 (Co _{max} $\simeq 0.2$)	$2 \cdot 10^{-4}$	1.3321	2.565	0.5183	0.182
RK 2–2 (Co _{max} $\simeq 0.4$)	$4\cdot 10^{-4}$	1.3321	2.565	0.5183	0.182
RK 3–4 (Co _{max} $\simeq 0.2$)	$2\cdot 10^{-4}$	1.3321	2.565	0.5183	0.182
RK 3–4 (Co _{max} $\simeq 0.4$)	$4 \cdot 10^{-4}$	1.3321	2.566	0.5183	0.182
RK 3–4 (Co _{max} $\simeq 0.6$)	$6 \cdot 10^{-4}$	1.3321	2.564	0.5183	0.183
RK 4–5 (Co _{max} $\simeq 0.2$)	$2 \cdot 10^{-4}$	1.3321	2.564	0.5183	0.182
RK 4–5 (Co _{max} $\simeq 0.4$)	$4\cdot 10^{-4}$	1.3347	2.565	0.5182	0.182
RK 4–5 (Co _{max} $\simeq 1.0$)	$8\cdot 10^{-4}$	1.3321	2.564	0.5183	0.182
rhoCentralFoam ($\mathrm{Co}_{max}\simeq 0.2$)	$2\cdot 10^{-4}$	1.3347	2.580	0.5215	0.182

Table 2 Cylinder at Re = 150, $M_{\infty} = 0.2$, G2-grid results. caafoam-m2

Table 3 Cylinder at Re = 150. Literature data.

Case	$\langle C_D \rangle$	$\Delta C_D \cdot 10^2$	ΔC_L	St
Muller [33]	1.34	2.6	0.52	0.183
Inoue and Hakateyama [34]	1.32	2.6	0.52	0.183
Williamson [47] (Exp.)	_	_	_	0.18

	U	, .		
	RK 4–5 coarse	RK 4–5 fine	rhoCentralFoam (fine)	Inoue [40]
$\langle C_D \rangle$	1.5806	1.5920	1.5859	1.5519
$\langle C_L \rangle$	± 0.0759	± 0.0753	± 0.0749	± 0.0689
$2\Delta C_D$	0.2216	0.2282	0.2281	0.2377
$2\Delta C_L$	0.8286	0.8479	0.8456	0.8575
St	0.153	0.144	0.155	0.150

Table 4 Side–by–side square cylinders at Re = 150, $M_{\infty} = 0.2$. Force coefficients.

Table 5 $\,$

Square cylinder in tandem configuration at Re = 150, $M_{\infty} = 0.2$. Force coefficients. Upstream cylinder

Case	$\langle C_D \rangle$	$2\Delta C_D \cdot 10^4$	$2\Delta C_L$	St
RK 4-5 coarse	1.2753	2.0	0.0378	0.134
RK 4-5 fine	1.2803	2.1	0.0384	0.134
rhoCentralFoam (fine)	1.2805	2.1	0.0383	0.134
Inoue et al. $[42]$	1.2794	_	_	0.133

 $Downstream \ cylinder$

Case	$\langle C_D \rangle$	$2\Delta C_D \cdot 10^3$	$2\Delta C_L$	St
RK 4-5 coarse	-0.1936	1.50	0.106	0.134
RK 4-5 fine	-0.1959	1.54	0.1068	0.134
rhoCentralFoam (fine)	-0.1961	1.53	0.1065	0.134
Inoue et al. [42]	-0.1945	_	—	0.133